ON THE OCCURRENCE OF DYNAMIC INSTABILITY IN INCIPIENT AND DEVELOPING HURRICANES

M. A. ALAKA

National Hurricane Research Project, U.S. Weather Bureau, Miami, Fla.

[Manuscript received August 29, 1961; revised November 22, 1961]

ABSTRACT

Observations made by the specially instrumented aircraft, operated by the National Hurricane Research Project, establish the occurrence of dynamic instability, notably in the form of anomalous winds in the upper troposphere above hurricane Daisy, shortly after its inception. It is inferred that the dynamic instability released by these anomalous winds, which represent anticyclonic rotation in space, triggered Daisy's development.

Since the observed dynamic instability occurred on a mesoscale, the above inference is not amenable to direct verification from synoptic maps. However, synoptic conditions favorable for the development of anomalous winds are discussed and it is found that these conditions prevailed in the upper troposphere directly above Daisy and Gracie a short time before they reached hurricane intensity.

The role of negative absolute vorticity is shown to vary. In the presence of anomalous winds it is a stabilizing factor which is nonetheless important in channeling outflow at the top of the hurricane. With normal winds, negative absolute vorticity is a destabilizing agent and some evidence is presented that it may also be responsible for initiating the development of certain hurricanes.

1. INTRODUCTION

Hurricanes are thermally driven circulations whose main source of energy is the latent heat of condensation. To make this heat source available, organized ascent of air must occur in the hurricane core, and there are compelling reasons to belive that a substantial proportion of the ascending air must come from the surface layers since only air from these layers contains enough heat and moisture to bring about density changes of the magnitude observed in hurricanes [10].

In addition, hurricanes are energy exporting systems. The mechanical energy they generate is only a small fraction of the heat released inside them, and the maintenance of their circulation is dependent on the removal of this heat excess. Palmén and Riehl [9] have shown that no cold source of sufficient magnitude to absorb this excess of heat exists within the hurricane circulation. Heat removal must therefore be accomplished by outflow to the surrounding atmosphere.

For the above reasons, it would seem that among the essential requirements for hurricane occurrence and maintenance is a mechanism which is capable of inducing organized ascent of air from the surface and of evacuating this air at the top of the storm. Whereas the necessity for such a mechanism has been recognized, its precise nature and the combination of circumstances attending its release have so far defied an exact formulation which is backed by observational evidence.

The purpose of this present paper is to provide observational evidence in support of the hypothesis that the mechanism in question is in the nature of dynamic instability which, under suitable circumstances, develops above a pre-existing disturbance in the easterlies and triggers its intensification into a hurricane. This concept is, of course, not new. For instance, Sawyer [11] and Kleinschmidt [7] have both invoked it in explaining hurricane formation. Both these authors, however, visualize dynamic instability to be released with the occurrence of negative absolute vorticity. On the other hand, it has been the opinion of the author [2] that the mechanism in question is likely to be in the form of anomalous winds which represent anticyclonic rotation in space. A measure of observational evidence now exists in support of this view and is presented below.

2. SYNOPTIC HISTORY AND OBSERVATIONAL SOURCES

During the past few years, the specially instrumented aircraft, operated by the National Hurricane Research Project (NHRP) for the purpose of making detailed observations in and near hurricane cores, have provided a valuable new source of information for the study of these atmospheric phenomena.[1]

Among the most successful missions accomplished were those flown in and around hurricane Daisy which presented a well-defined and concentrated wind circulation and a clear-cut radar configuration, facilitating the location of the storm core.

[1] A discussion of the characteristics and properties of the instrumentation has been given by Hilleary and Christensen [6].

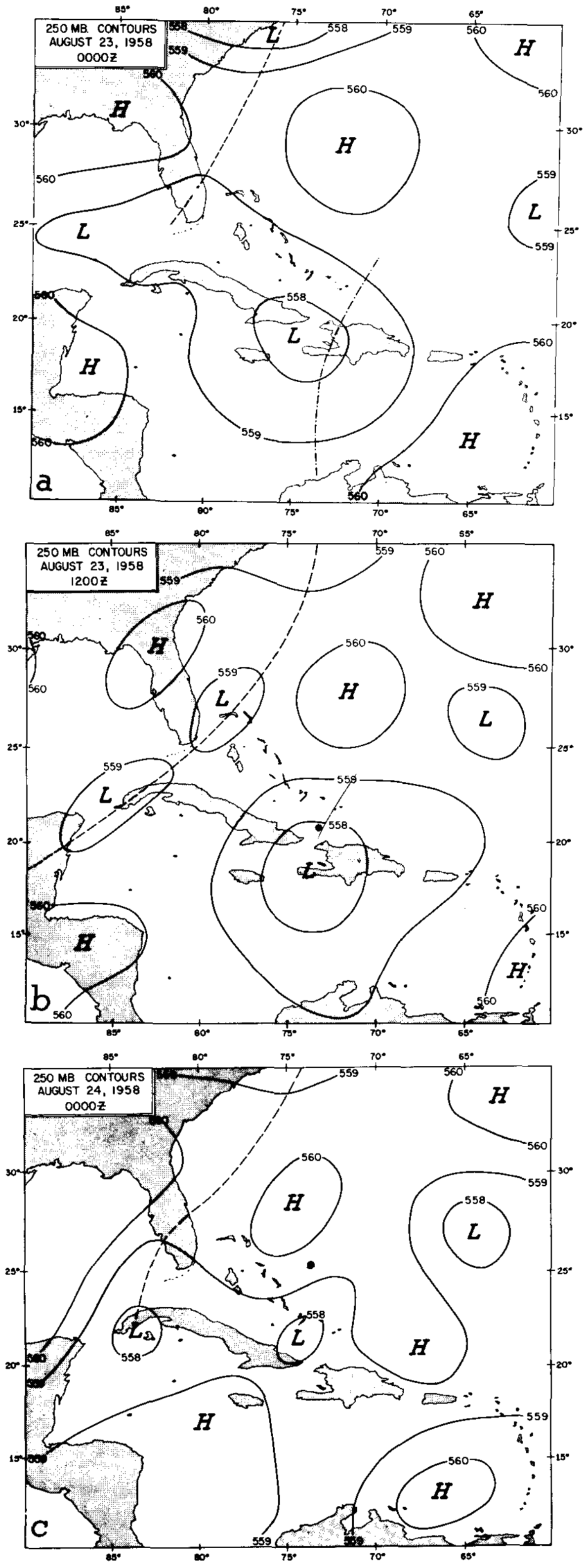

FIGURE 1.—250-mb. contours: (a) 0000 GMT, August 23, 1958. The dashed-dotted line shows the surface position of the easterly wave which later developed into hurricane Daisy. (b) 1200 GMT, August 23, 1958. The black dot shows the surface position of the low pressure center. (c) 0000 GMT, August 24, 1958. The black dot shows the surface position of the tropical disturbance which reached hurricane intensity on the next day.

Hurricane Daisy developed on August 24, 1958, in an easterly wave which had moved westward from the eastern Atlantic Ocean. At 0000 GMT, August 23, the wave was located near the Windward Passage and was of average amplitude. Twelve hours later a weak low pressure center appeared some distance to the north of Haiti. At 0000 GMT, August 24, the minimum pressure was about 1010 mb. Figure 1 shows the position of the surface disturbance on the above dates superposed on the corresponding 250-mb. contour fields. Rapid intensification occurred at about the time of the last map, and shortly after, a U.S. Navy reconnaissance plane located an eye formation with maximum winds of about 50 kt. and a minimum pressure of 1002 mb. By 1200 GMT, August 25, the maximum winds in the core were 70 kt. It was at this time that the NHRP aircraft made their first penetration into Daisy. During the next few days, the hurricane remained fairly close to the Florida coast and to the Operations Base of NHRP which, at that time, was situated in West Palm Beach, Fla. This allowed several lengthy missions to be flown at different levels in and around the hurricane core on four consecutive days ending on August 28 when Daisy had reached and passed its peak intensity.

Among the elements measured by the aircraft were the wind, the temperature, the radio altitude, and the pressure altitude. Quasi-instantaneous values of these parameters were punched on cards at specified intervals ranging from 10 seconds away from the core to 2 seconds in the core. The punched cards were then evaluated by machine processing and the various parameters were plotted on a coordinate system fixed with respect to the center of the storm.

The data selected and processed in the above manner represent an impressive amount of detailed information which has already provided material for several studies including a detailed description of the structure of hurricane Daisy [4]. They constitute one of the principal observational sources which will be utilized in discussing the role of dynamic instability in triggering hurricane formation.

3. OBSERVATIONAL EVIDENCE FOR THE OCCURRENCE OF DYNAMIC INSTABILITY

To determine the occurrence of dynamic instability above the incipient and developing hurricane, it is necessary to identify the circumstances attending the release of this type of instability. It would of course be desirable if the required criterion could be derived for the general case in which both the temporal and spatial variations of the various parameters are taken into consideration. Such an approach would be all but mathematically intractable. Complications are greatly reduced if the upper flow, where dynamic instability is expected to occur, is approximated to a large steady circular vortex. This approximation is not far-fetched since intensification into a hurricane is generally observed to occur when the tropical disturbance is situated under an upper anticyclone. The approximation takes into account the curvature of the upper air flow which is of crucial importance. Under such conditions, it has been shown [3, 11, 13] that the criterion for the release of dynamic instability may be written with sufficient approximation

$$\zeta_a\left(\frac{2V}{R_t}+f\right)<0 \tag{1}$$

where ζ_a, V, R_t, and f respectively denote the absolute vorticity, the wind speed, the trajectory radius of curvature, and the Coriolis parameter. This criterion was utilized to determine the occurrence of dynamic instability in hurricane Daisy.

Figures 2 a-c [4] represent the wind field in the upper troposphere above hurricane Daisy on August 25, 26, and 27, 1958 obtained by analyzing aircraft observations referred to in section 2. From this analysis, values of wind speed and direction were plotted on a rectangular grid with points 20 n. mi. apart, and computations of vorticity and the quantity $2V/R_t$ were made on the IBM 650. The latter quantity was obtained from the following relations:

If u and v denote the westerly and southerly components of the wind, and if we define

$$\psi=\tan^{-1}\frac{u}{v} \tag{2}$$

then

$$\frac{1}{R_t}=-\frac{d\psi}{ds}=\cos^2\psi\left(\frac{u}{v^2}\frac{dv}{ds}-\frac{1}{v}\frac{du}{ds}\right)=\frac{1}{V^3}\left(u\frac{dv}{dt}-v\frac{du}{dt}\right) \tag{3}$$

If the motion of the storm is represented by the vector $\mathbf{C}$ with components c_x and c_y in the east and north directions respectively, and if we assume steady state conditions,

$$\frac{2V}{R_t}=\frac{2}{V^2}\left\{u\left[(u-c_x)\frac{\partial v}{\partial x}+(v-c_y)\frac{\partial v}{\partial y}\right]\right.$$
$$\left.-v\left[(u-c_x)\frac{\partial w}{\partial x}+(v-c_y)\frac{\partial u}{\partial y}\right]\right\} \tag{4}$$

Figures 3 a-c represent the vorticity fields; shaded areas mark regions of negative absolute vorticity.[2] Figures 4 a-c represent corresponding fields of the quantity $2V/R_t$; the shading denotes areas where the wind is anticyclonic with a speed numerically greater than the quantity $fR_t/2$. Such winds represent an anticyclonic rotation in space, i.e., opposite to the earth's rotation, and have been termed anomalous winds; their occurrence, properties, and significance were recently discussed by the author [3].

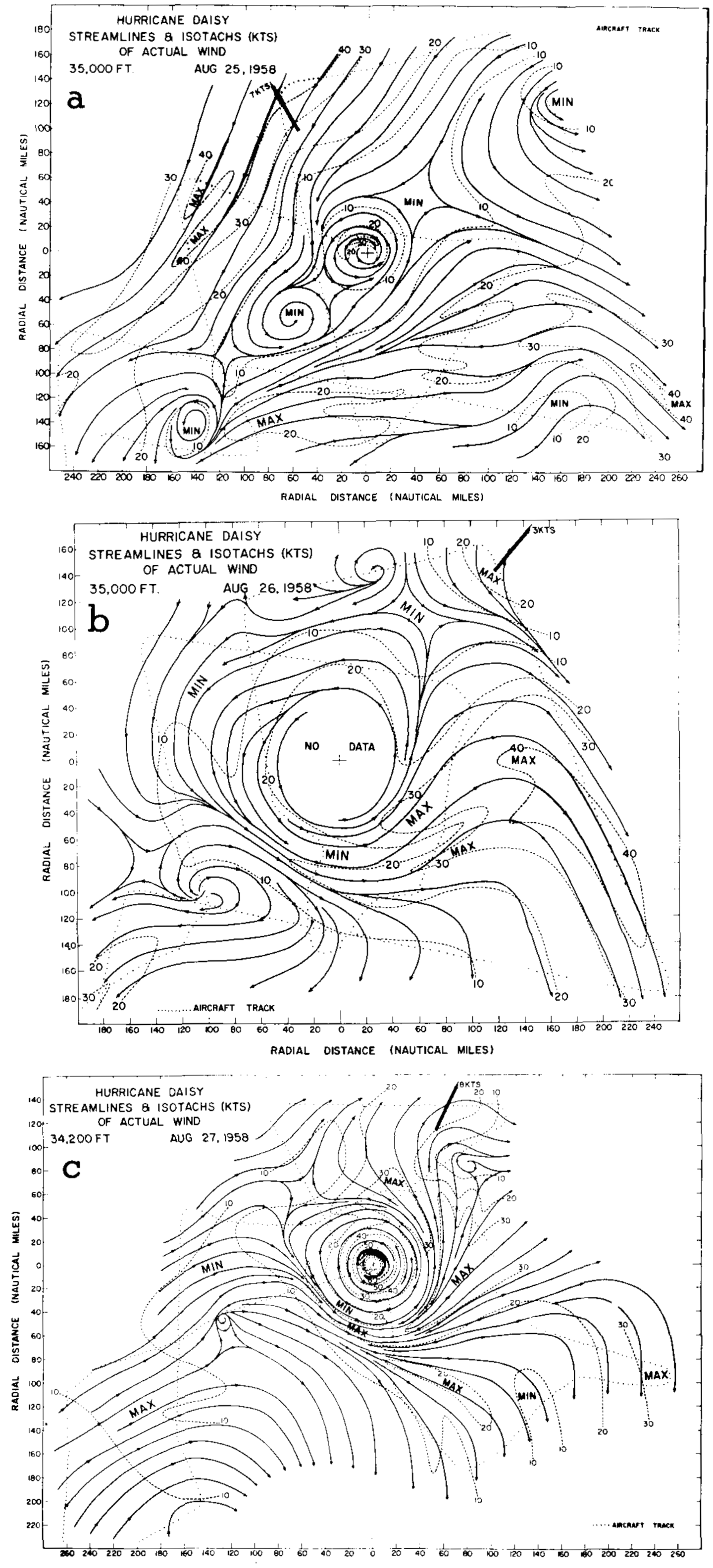

FIGURE 2.—Wind field around hurricane Daisy [4]: (a) at 35,000 ft. on August 25, 1958; (b) at 35,000 ft. on August 26, 1958; (c) at 34,200 ft. on August 27, 1958. (Pressure altitude, U.S. Standard.)

[2] In view of the comparatively small area under consideration the Coriolis parameter is considered constant with a value of 7×10^{-5} sec.$^{-1}$.

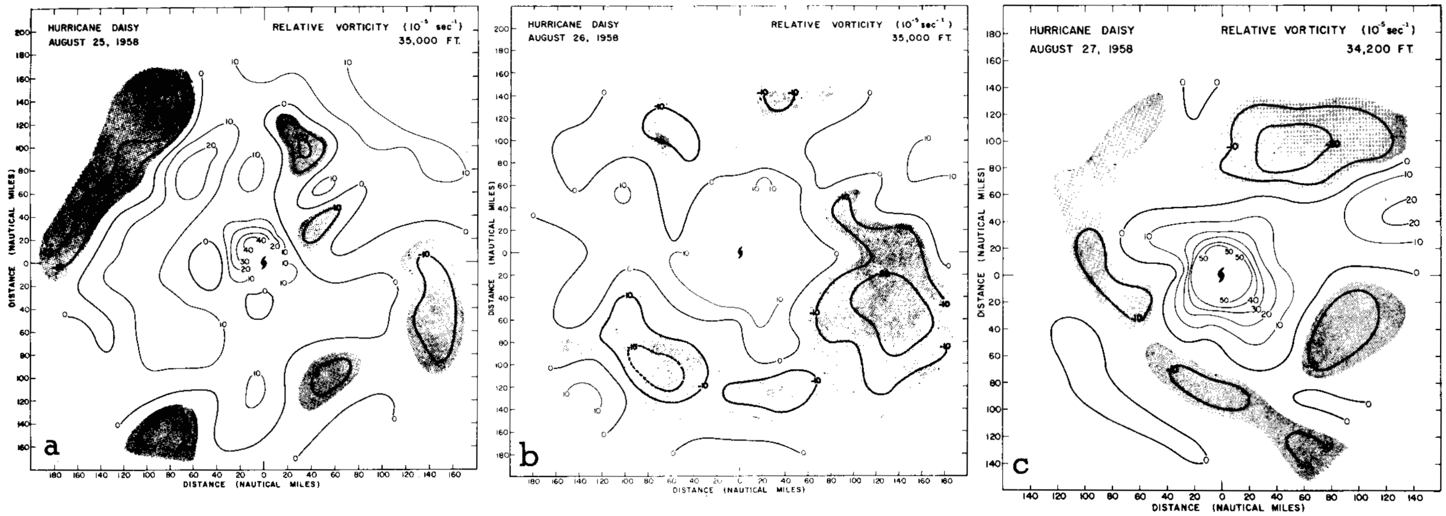

FIGURE 3.—Field of relative vorticity corresponding to the wind fields in figure 2 (a-c). Shading denotes regions of negative absolute vorticity.

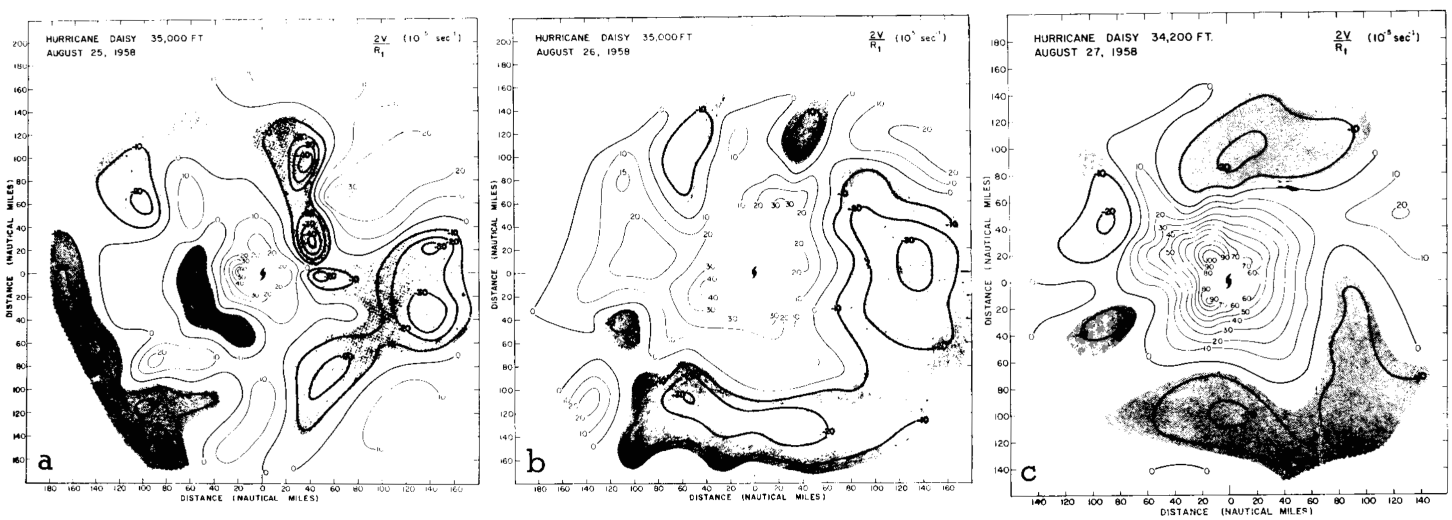

FIGURE 4.—Field of the quantity $2V/R_t$ corresponding to the wind fields of figure 2 (a-c). Shading denotes regions of anomalous winds.

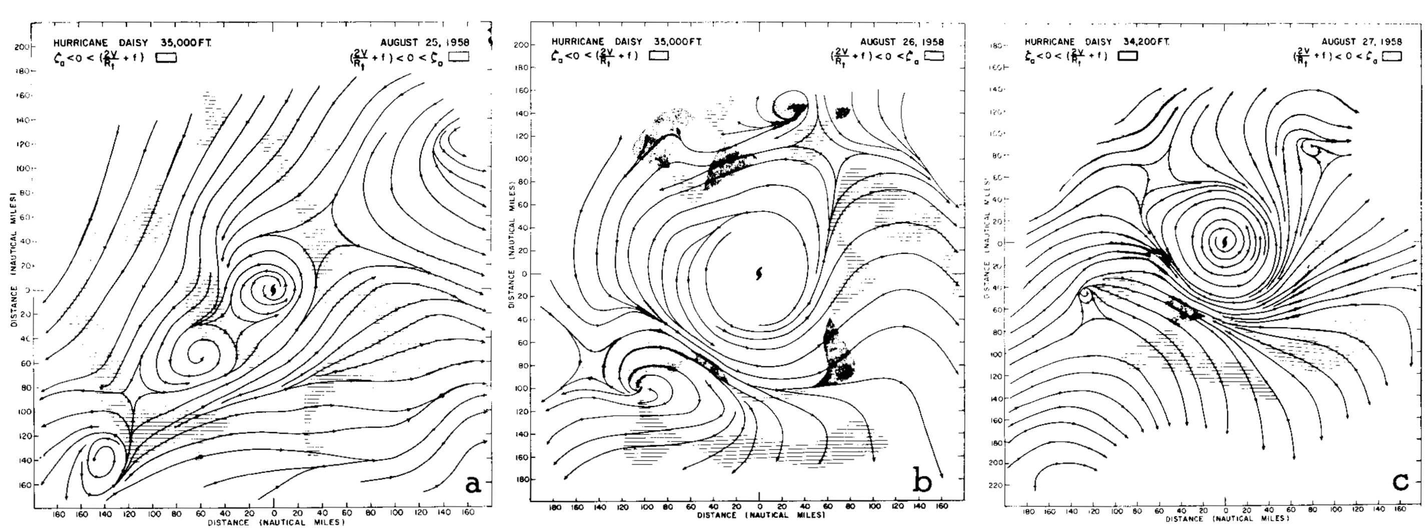

FIGURE 5.—Dynamic instability shaded areas superimposed on the streamlines around hurricane Daisy: (a) at 35,000 ft. on August 25, 1958; (b) at 35,000 ft. on August 26, 1958; (c) at 34,200 ft. on August 27, 1958. (Pressure altitude, U.S. Standard.)

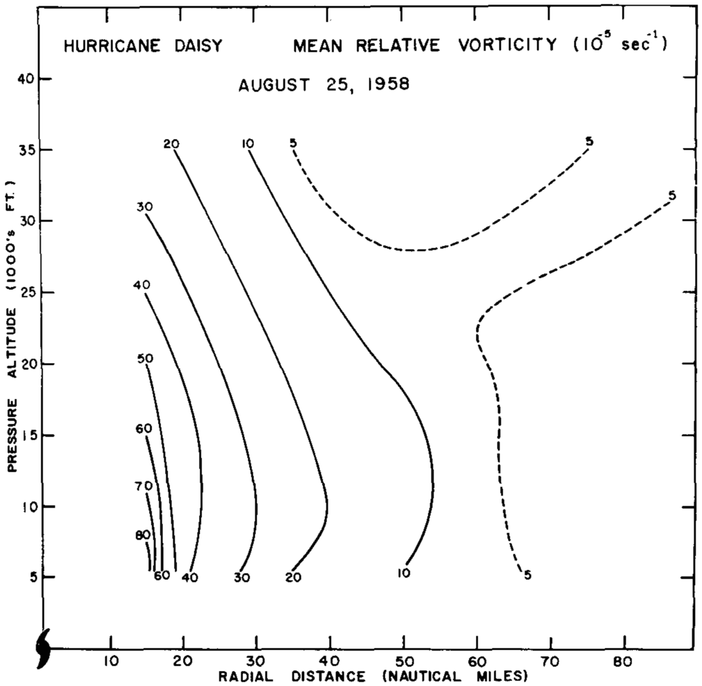

FIGURE 6.—Cross-section of mean relative vorticity around hurricane Daisy on August 25, 1958, obtained from observations by NHRP aircraft at 35,000, 15,600, and 5,500 ft. (Pressure altitude, U.S. Standard.)

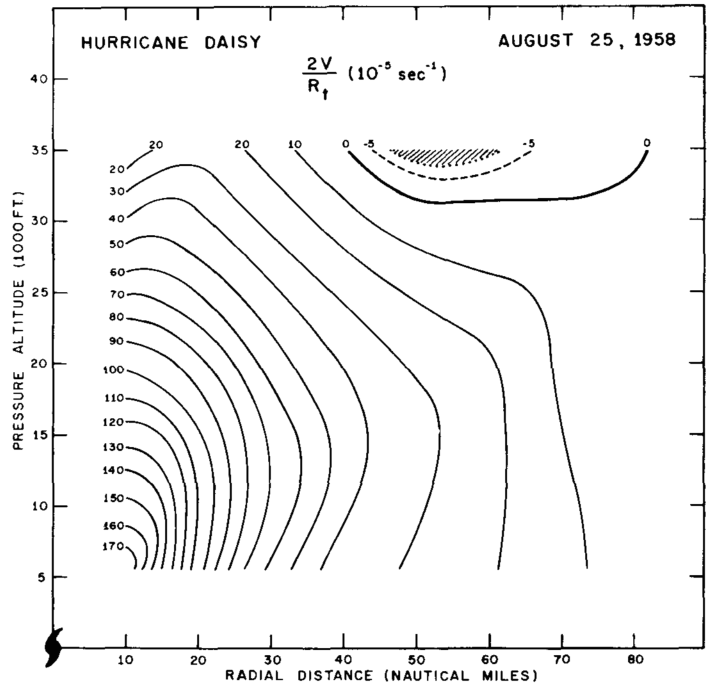

FIGURE 7.—Cross-section of the mean value of $2V/R_t$ around hurricane Daisy on August 25, 1958, obtained from observations by NHRP aircraft at 35,000, 15,600, and 5,500 ft. (Pressure altitude, U.S. Standard.)

Figures 3 and 4 show that in the upper troposphere, above hurricane Daisy, anomalous winds and negative absolute vorticity generally occurred in overlapping areas and dynamic instability, according to inequality (1) therefore occurred on the outer fringes of these areas. These are indicated by the shaded parts of figures 5 a-c.

The most noteworthy aspect of the regions of instability is their association with outflow from the hurricane. On the 25th this occurred both in the left front and right rear quadrants of the hurricane and coincided in both places with a maximum in the wind speed (fig. 2a).

On the 26th (fig. 5b) the outflow was more organized and occurred mainly along a channel which closely followed a narrow strip of instability extending from an anticyclonic twirl to the southwest of the hurricane, running south of the center, then curving anticyclonically to the north, east, and southeast following the streamlines. In this region, figure 2b shows a jet-like configuration which closely follows the pattern of instability.

It is thus seen that upper tropospheric outflow from hurricane Daisy was closely related to dynamic instability which in turn was related to the anticyclonic eddies surrounding the cyclonic core of the hurricane. This association of upper hurricane outflow with anticyclonic eddies was noted by Simpson [12] in connection with hurricane Dolly.

4. ROLE OF ANOMALOUS WINDS IN TRIGGERING HURRICANES

The question which remains to be asked is whether dynamic instability occurred prior to the development of the hurricane, was thus instrumental in its formation, or whether it was a product of hurricane development. To provide an unequivocal answer to this question would require detailed observations just prior to and at the time the tropical disturbance was transformed into a hurricane. Such observations are not available and we must therefore base our conclusions upon such indirect evidence as the data provide.

We note that on August 25 (fig. 5a), dynamic instability was generated almost entirely by anomalous winds, whereas on August 27 (fig. 5c), it was about equally due to anomalous winds and to negative absolute vorticity. The preponderance of the effect of anomalous winds in producing dynamic instability on the 25th is even more clearly seen from figures 6 and 7 which represent cross-sections of ζ and $2V/R_t$ averaged around the hurricane. Averaging completely masks the occurrence of negative absolute vorticity but not that of anomalous winds.

The increase, between the 25th and the 27th, of the relative share of negative absolute vorticity in producing dynamic instability is due to the fact that the area covered by negative absolute vorticity increased appreciably

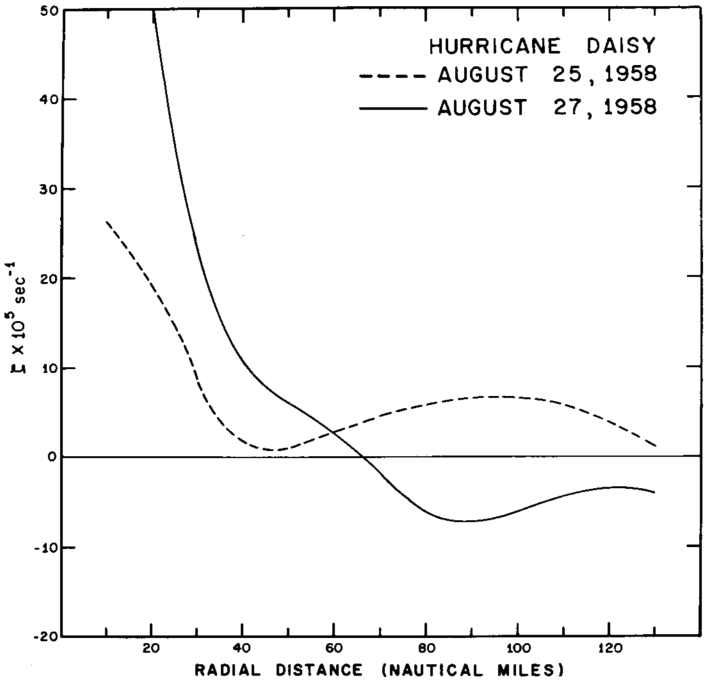

FIGURE 8.—Mean radial profile of relative vorticity at 35,000 ft. (pressure altitude, U.S. Standard) around hurricane Daisy on August 25 and 27, 1958.

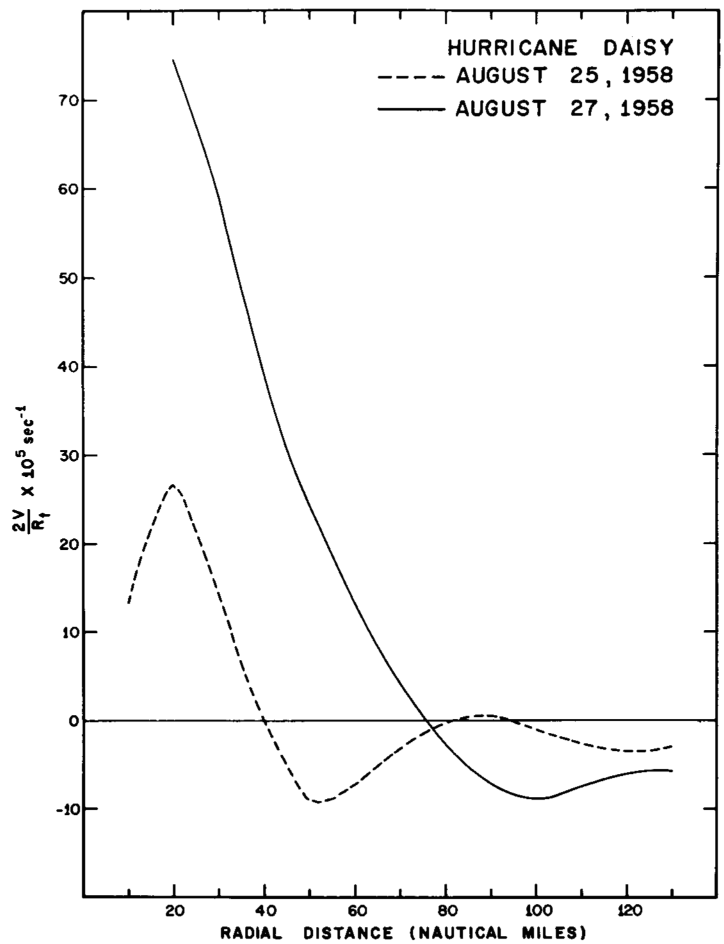

FIGURE 9.—Mean radial profile of $2V/R_t$ at 35,000 ft. (pressure altitude, U.S. Standard) around hurricane Daisy on August 25 and 27, 1958.

between August 25 and 27 (fig. 3), whereas no such trend is noticeable from figure 4 with regard to the area covered by anomalous winds. Figures 8 and 9 represent the mean radial profile of ζ and $2V/R_t$ in the upper troposphere on these dates. For the 25th, all parts of the vorticity profile are above the zero line, while for the 27th an appreciable portion of the profile is below the line. In contrast, nearly an equal portion of the profile of $2V/R_t$ shows negative values for the 25th and the 27th, the only difference being that, on the later date, these values are located farther away from the center, thus reflecting the increasing horizontal dimensions of the central cyclonic vortex.

To the extent that it is legitimate to extrapolate backward in time, we may conclude that in the case under consideration, the occurrence of anomalous winds preceded that of negative absolute vorticity and was present at the time the tropical disturbance was transformed into a hurricane, which is roughly 24 hours before the first aircraft observations were made. The instability released by these anomalous winds would then have provided the necessary dynamic mechanism for triggering the observed rapid transformation.

The above conclusion is supported by the synoptic situation in the upper troposphere above the incipient hurricane. It should however be pointed out at this juncture that we are now dealing with two different scales of motion. Figures 3 and 4 show that both negative absolute vorticity and anomalous winds are mesoscale quantities which occur in narrow strips 1° or 2° of latitude wide, and would ordinarily filter through the usual synoptic network. Therefore, to detect the occurrence of anomalous winds by direct computation from ordinary synoptic maps may not yield conclusive results, especially in the absence of a dense network of observations. Lacking such a network and aircraft observations on a scale similar to that from which figures 3 and 4 were computed, the best we can do is to determine whether synoptic conditions were propitious to the occurrence of anomalous winds at the critical time when the disturbance was transformed into a hurricane.

In a recent article [3] the author has inquired into the circumstances leading to the development of anomalous winds and has suggested that these are likely to occur when the pressure gradient force in an anticyclone increases to a value very near the maximum for gradient motion expressed by the quantity $-fR_t/4$. Briefly, the argument on which this suggestion is based is the following:

From figure 10 it is seen that normal and anomalous winds meet when the speed $V=f/2k'_t$ where $k'_t=-k_t=-1/R_t$; this corresponds to the maximum pressure gradient $f^2/4k'_t$. From this point, the two wind regimes branch out so that the difference between gradient wind speed in the two regimes increases with decreasing pressure gradient.

Let A be the position of a particle in an anticyclonic air stream which is initially in normal gradient equilibrium, and let this equilibrium be disturbed by an increase in the pressure gradient. Two cases may be discussed:

a. The pressure gradient force (b_n) increases from P to a value P_1 which is well below the maximum $f^2/4k'_t$. The wind, having become subgradient, the air particle moves down the gradient and accelerates. Because of its inertia, the particle may slightly overshoot the equilibrium speed at B, in which case it will oscillate with decreasing amplitude about this position until balance is finally reached.

b. The pressure gradient force increases from P to a value P_2 which is very nearly equal to the maximum. In this case, the speed of the accelerating particle, by overshooting the equilibrium position, may reach the value B_3 which corresponds to the anomalous regime. Whereas at B_2 the speed of the particle is supergradient, at B_3 it is subgradient for the same pressure gradient. Thus by overshooting the critical wind speed $f/2k'_t$, the particle tends to continue to move toward lower pressure and sustain further acceleration. In short, the motion of the particle becomes unstable.

The sequence of upper-air maps of figure 1 strongly suggests that intensification into a hurricane occurred only when conditions became favorable for the development of anomalous winds above the surface disturbance. Figures 1a and 1b show this disturbance under upper cyclonic flow where, clearly, anomalous winds do not occur. On the other hand, figure 1c, which corresponds to the time of most rapid intensification, shows the incipient hurricane under the rim of an upper high pressure cell. This, of course, is a necessary but not sufficient condition for the development of anomalous winds which, as we discussed above, require anticyclonic trajectory curvatures which are near the maximum possible for the pressure gradient. To determine to what extent this condition is satisfied in the present case would require an accurate determination of both trajectory curvatures and contour gradients; this is hardly possible in the case of hurricane Daisy in view of the sparseness of the upper synoptic data in the crucial area around the storm. A rough estimate of trajectory curvature was however obtained by constructing a sequence of 12-hourly upper streamline maps from 0000 GMT on the 23d to 1200 GMT on the 24th. In this manner, consideration of continuity was brought to bear on the analysis, thereby increasing the accuracy of the streamlines which were constructed by the isogon technique. We write

$$k_t=k_s+\frac{1}{V}\frac{\partial\psi}{\partial t} \tag{5}$$

where k_s denotes the streamline curvature and $\partial\psi/\partial t$ is

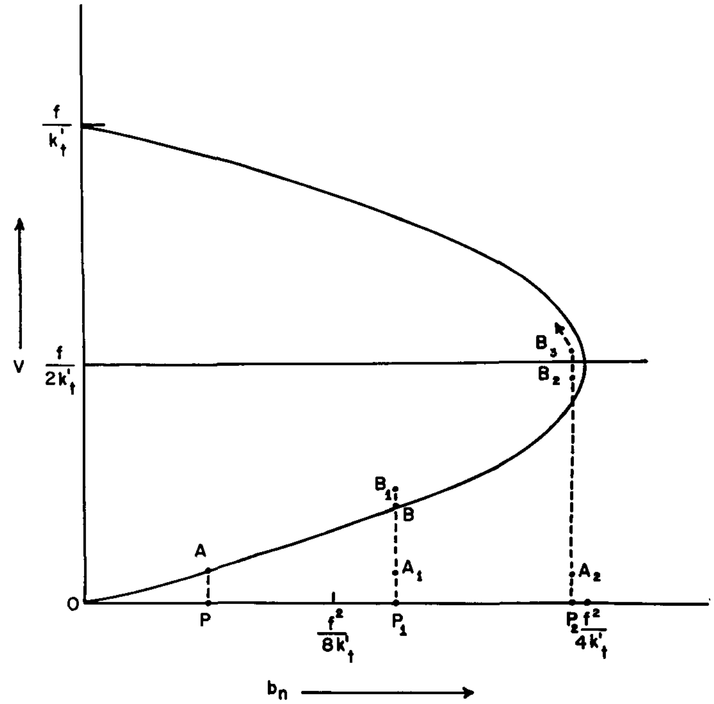

FIGURE 10.—Distribution of gradient anticyclonic wind with pressure gradient force, illustrating a possible mechanism for the development of anomalous winds (see text).

the local turning of the wind direction with time, taken positive for a counterclockwise turning [5].

At 0000 GMT, August 24, the contour gradient normal to the streamlines above the surface position of the disturbance was estimated at 5.5 ft. per degree of latitude. The maximum anticyclonic trajectory curvature ($k_{t\ max}$) corresponding to this gradient at latitude 25° is -0.7×10^{-8} cm.$^{-1}$. From the streamline map k_s at this point was -3.0×10^{-8} cm.$^{-1}$. If the condition for the development of anomalous winds is satisfied, i.e., if $k_t \approx k_{t\ max}$, then from equation (5)

$$\frac{1}{V}\frac{\partial\psi}{\partial t}\approx(-0.7+3.0)\times10^{-8}=2.3\times10^{-8}\text{ cm.}^{-1}$$

If V is taken to be 15 kt., the above equation corresponds to a 90° backing of the wind in 24 hours. From the streamline maps the 24-hour backing of the wind from 1200 GMT on the 24th to 1200 GMT on the 25th, above the surface position of the incipient hurricane shown in figure 1c, was estimated to be about 100°.

The combination of tight contour gradient and strong anticyclonic trajectory curvature in the upper troposphere was again in evidence above the surface position of hurricane Gracie (1959), at the time of its inception. Fortunately, this occurred in the vicinity of a reasonably good network of synoptic stations so that a more conclusive test of the criterion suggested above could be made.

According to a Navy report [14] Gracie formed on an easterly wave which was first detected near the African

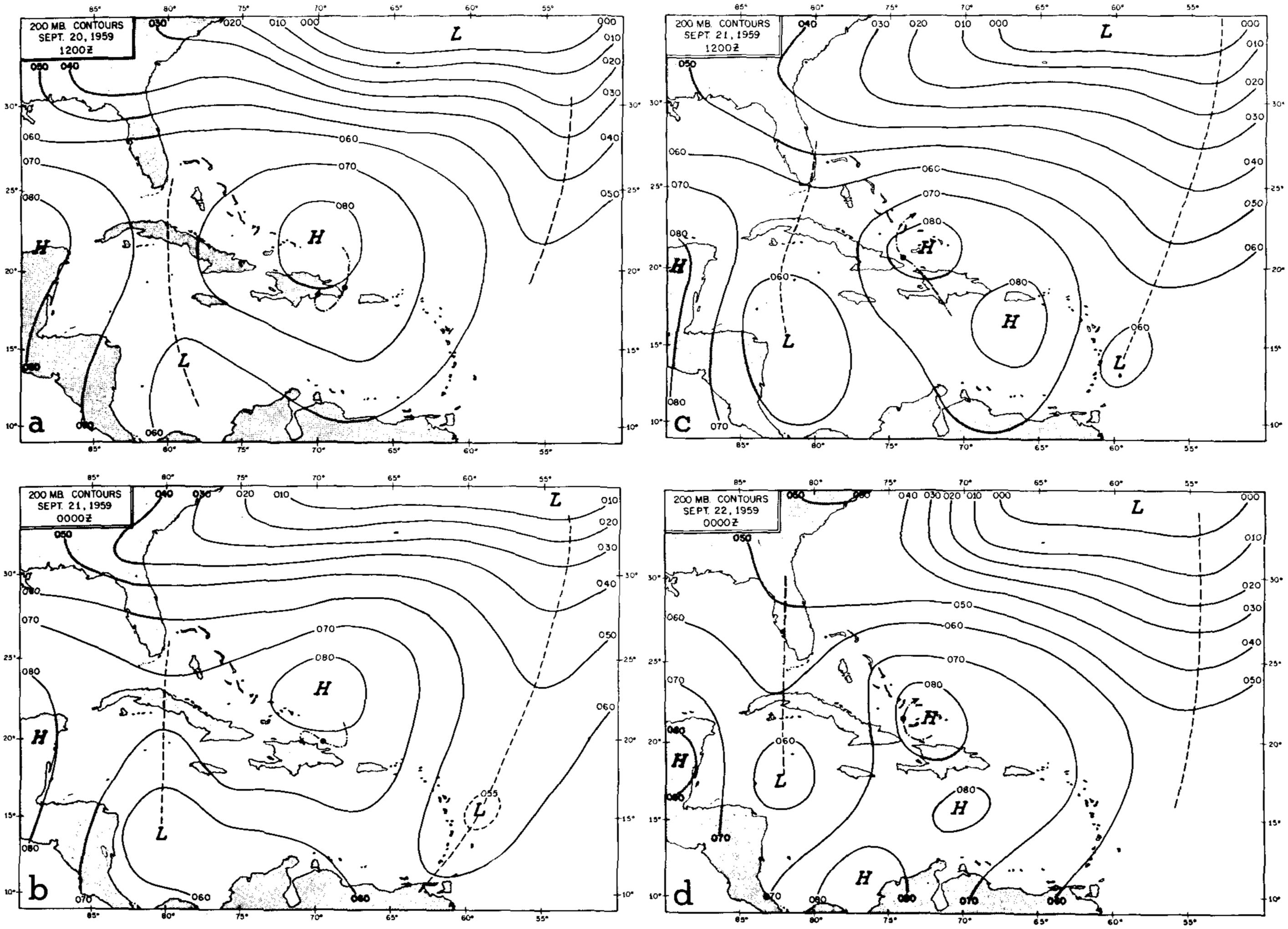

Figure 11.—200-mb. contours: (a) 1200 gmt, September 20, 1959; (b) 0000 gmt, September 21, 1959; (c) 1200 gmt, September 21, 1959; (d) 0000 gmt, September 22, 1959. The black dot shows the current surface position of the disturbance from which hurricane Gracie developed; the dashed-dotted curve represents air trajectory directly above the surface position.

coastline on September 11, 1959. At 1200 gmt on the 17th, ship reports indicated that the wave was increasing in intensity 750 mi. to the east of Antigua. Daily reconnaissance flights by Navy aircraft from the 18th to the 21st revealed little change of the low-level conditions which were characterized by a weak center with a sea level pressure of about 1008 mb., easterly winds of 20–30 kt. to the north of the center, and weak westerly winds south of it.

During the afternoon and evening of the 21st, reconnaissance reports indicated that development was taking place. Surface pressures began falling slowly and were accompanied by abnormally heavy precipitation. The first warning on Gracie was issued at 1600 gmt on the 22d. Reconnaissance aircraft reported a radar eye at 1645 gmt. In about 5 hours winds increased from 45 to 75 kt., the central surface pressure dropped to 997 mb., and a radar eye became clearly defined. Gracie had become a full-fledged hurricane.

Figures 11 a-d show the 200-mb. contours on the day the rapid development of Gracie occurred, as well as on the two preceding days. The figures also give particle trajectories above the surface position of the disturbance. All maps show the disturbance under an upper anticyclone. Figures 11a and 11b, however, indicate a fairly slack contour gradient and almost straight trajectories above the surface position of the storm. Obviously the criterion, formulated above for the development of anomalous winds, was not satisfied. At 1200 gmt on the 21st (fig. 11c), the picture had changed. The storm was under a tight 200-mb. contour gradient and the trajectory curvature began to be strongly anticyclonic. At 0000 gmt on the 22d (fig. 11d) the 200-mb. contour gradient directly above the storm can be conservatively estimated at 20 ft. per degree of latitude, corresponding to a minimum radius of curvature of more than 500 km. The radius of trajectory curvature directly above the incipient hurricane was manifestly less than this quantity and the criterion for the development of anomalous winds was satisfied. Fourteen hours later, the first Gracie warning was issued.

5. THE ROLE OF NEGATIVE ABSOLUTE VORTICITY IN HURRICANE DEVELOPMENT

We have noted from figures 3 and 4 that even in the early stages of hurricane development anomalous winds and negative absolute vorticity occur in overlapping areas. This represents an interesting situation which deserves comment.

Traditionally meteorologists are accustomed to consider negative absolute vorticity as a destabilizing factor, which indeed it is under normal conditions. However in the presence of anomalous winds, its role is reversed and, as can be seen from inequality (1), it becomes a stabilizing factor. Its importance in this novel capacity is however not to be underestimated. In the absence of negative absolute vorticity all the shaded areas in figure 4 would be unstable, and it is unlikely that organized outflow channels could be maintained in such a situation in view of the large lateral mass exchange which would occur in these areas. The development of negative absolute vorticity in the manner shown in figure 3 helps concentrate instability and thus promotes organization of the outflow into the well-defined channels observed in hurricanes.

The effect of negative absolute vorticity in hurricanes is however not exclusively stabilizing. As can be seen from figure 5, negative absolute vorticity occurs in small areas where the wind is not anomalous; such areas are unstable. Furthermore, there are cases in which the initial instability responsible for triggering hurricane formation appears to be attributable to negative absolute vorticity rather than to anomalous winds. Hurricane Janice (1958) is one such case. Figure 12 shows the 200-mb. contour and isotach fields at 1200 GMT on October 6, 1958, 6 hours before hurricane winds were first observed. The position of the incipient hurricane was directly below the warm side of a jet stream core where negative vorticity is known to occur [1]. In the present case, the anticyclonic wind shear above the surface position of the disturbance is estimated at 1.5×10^{-4} sec.$^{-1}$; this, coupled with the fact that the streamlines (not shown) were only slightly cyclonic, would indicate that negative absolute vorticity did in fact occur. The cyclonic streamlines and the configuration of the contours make it unlikely that anomalous winds could have developed in this area at this time.

Thus Daisy and Gracie, on the one hand, and Janice, on the other hand, represent two categories of hurricanes. Both categories are triggered by dynamic instability in the upper levels. But in the case of Daisy and Gracie instability was initiated by the development of anomalous winds, whereas in the case of Janice the instability appears to have been initially due to negative absolute vorticity.

It would be interesting to study the similarities and differences in structure and behavior of the above two categories of hurricanes.

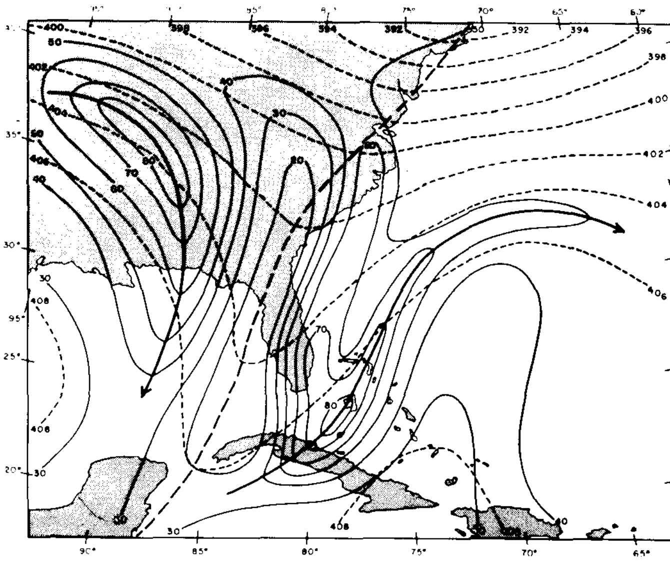

FIGURE 12.—200-mb. isotachs (solid lines) and contours (thick dashed lines) at 1200 GMT, October 6, 1958. Black dot shows the surface position of Janice 6 hours before hurricane winds were first reported.

6. CONCLUSION

We have attempted to demonstrate that dynamic instability is an essential factor in triggering hurricane formation. The initial release of this instability depends, at least partially, on the accidental drift of the proper upper flow over the surface disturbance. This would account for the comparative rarity of hurricanes. On the other hand, hurricane formation is closely linked to the convective bands which occur in association with the surface disturbance [8] and it is likely that instability develops as a result of the interaction between these convective bands and the upper-air flow. But the exact manner of this interaction and the comparative contribution of each of the two factors to the ultimate result is not known and offers a promising avenue for further research.

Once the hurricane is successfully triggered, dynamic instability is maintained by the circulation inside the hurricane. This built-in mechanism would account for the apparent ability of hurricanes to persist almost indefinitely so long as their source of energy, latent heat of condensation, is not cut off.

ACKNOWLEDGMENTS

The writer wishes to record his appreciation to Dr. José A. Colón for many helpful discussions, especially with regard to availability of data pertinent to this investigation; and to Dr. Stanley L. Rosenthal for his help in programming computations on the IBM 650. The writer also wishes to acknowledge his indebtedness to Mr. Daryl. T. Rubsam, Mrs. Miree Moore, Mr. A. M. Recht, Mr. R. Carrodus, and Mr. C. True.

REFERENCES

1. M. A. Alaka, "Case Study of an Easterly Jet Stream in the Tropics," *Tellus*, vol. 14, No. 1, Feb. 1958, pp. 24–42.
2. M. A. Alaka, "Dynamics of Upper Air Outflow in Incipient Hurricanes," *Geophysica*, vol. 6, No. 3–4, 1958, pp. 133–146.
3. M. A. Alaka, "The Occurrence of Anomalous Winds and Their Significance," *Monthly Weather Review*, vol. 89, No. 11, Nov. 1961, pp. 482–494.
4. J. A. Colón and Staff NHRP, "On the Structure of Hurricane Daisy (1958)," *National Hurricane Research Project Report* No. 48, U.S. Weather Bureau, 1961.
5. G. J. Haltiner and F. L. Martin, *Dynamical and Physical Meteorology*, McGraw-Hill Book Co., Inc., New York, 1957, 470 pp.
6. D. T. Hilleary and F. E. Christensen, "Instrumentation of National Hurricane Research Project Aircraft," *National Hurricane Research Project Report* No. 11, U.S. Weather Bureau, 1957.
7. E. Kleinschmidt, "Grundlagen einer Theorie der Tropischen Zyklonen," *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Ser. A., Band IV, 1951, pp. 53–72.
8. N. E. LaSeur, "The Role of Convection in Hurricanes," "Proceedings of the Second Technical Conference on Hurricanes," *National Hurricane Research Project Report* No. 50, U.S. Weather Bureau (in preparation).
9. E. Palmén and H. Riehl, "Budget of Angular Momentum and Energy in Tropical Cyclones," *Journal of Meteorology*, vol. 14, No. 2, Apr. 1957, pp. 150–159.
10. H. Riehl, *Tropical Meteorology*, McGraw-Hill Book Co., Inc., New York, 1954, 392 pp.
11. J. S. Sawyer, "Notes on the Theory of Tropical Cyclones," *Quarterly Journal of the Royal Meteorological Society*, vol. 73, 1947, pp. 101–126.
12. R. H. Simpson, "Structure of an Immature Hurricane," *Bulletin of the American Meteorological Society*, vol. 35, No. 8, Oct. 1954, pp. 335–350.
13. H. Solberg, "Le Mouvement d'Inertie de l'Atmosphère Stable et Son Rôle dans la Théorie des Cyclones," *Procès-Verbaux, l'Association Météorologique, UGGI, Edinbourg, 1936*, Part II, 1939, pp. 66–82.
14. U.S. Fleet Hurricane Forecast Facility, "Annual Tropical Storm Report," U.S. Navy, *OPNAV Report* 3140–9, Miami, Fla., 1959.